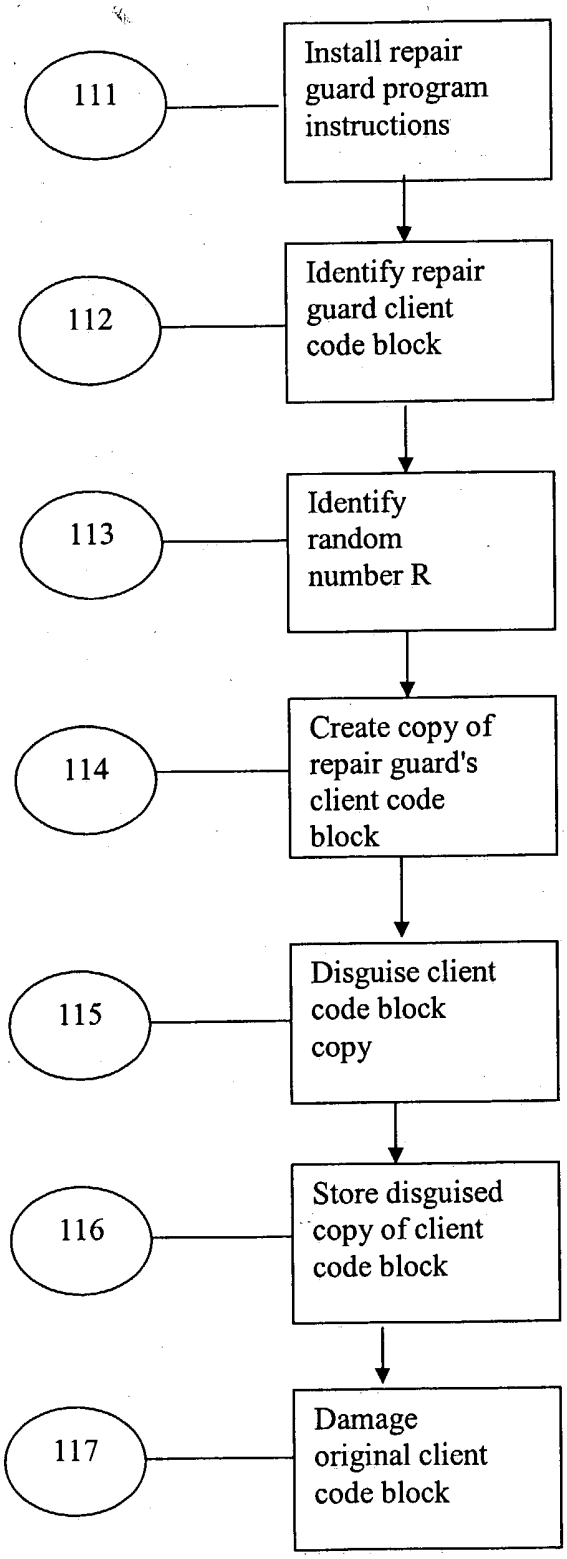

111
Install repair guard program instructions
112
Identify repair guard client code block
113
Identify random number R
114
Create copy of repair guard's client code block
115
Disguise client code block copy
116
Store disguised copy of client code block
117
Damage original client code block

FIG. 1A

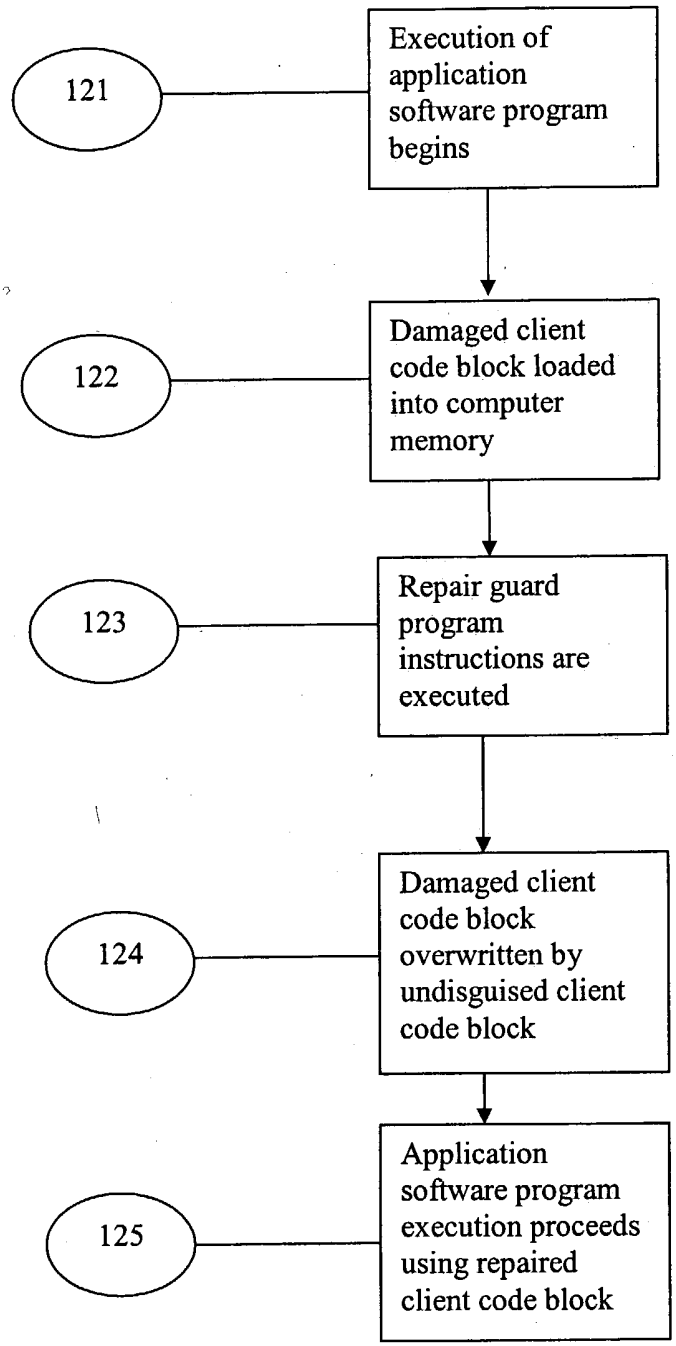

121
Execution of application software program begins
122
Damaged client code block loaded into computer memory
123
Repair guard program instructions are executed
124
Damaged client code block overwritten by undisguised client code block
125
Application software program execution proceeds using repaired client code block

FIG. 1B

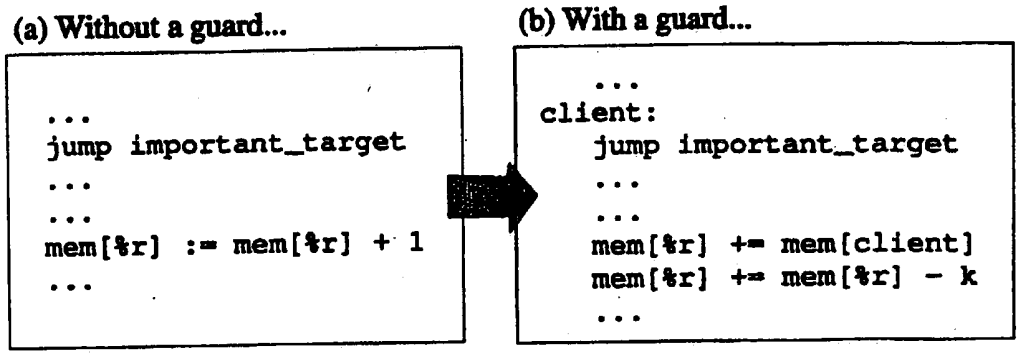

(a) Without a guard...
...
jump important_target
...
...
mem[%r] := mem[%r] + 1
...
(b) With a guard...
...
client:
jump important_target
...
...
mem[%r] += mem[client]
mem[%r] += mem[%r] - k
...

FIG. 2A

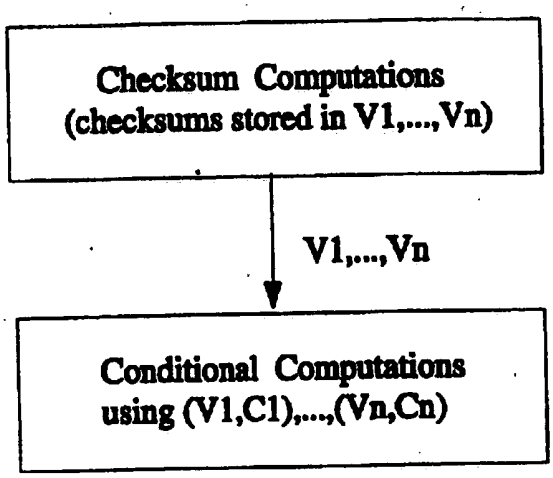

Checksum Computations
(checksums stored in V1,...,Vn)
V1,...,Vn
Conditional Computations
using (V1,C1),...,(Vn,Cn)

FIG. 2B

```
// template 1

        movl        $RANDOM_1, CHECKSUM_1 // RANDOM_1 = any integer
        movl        $START_1, TEMP_1
LABEL_1:
        Cmpl        $END_1, TEMP_1
        jg          LABEL_2
        addl        (TEMP_1), CHECKSUM_1
        addl        $RANDOM_2, TEMP_1 // RANDOM_2 in [3,5]
        jmp         LABEL_1
LABEL_2:

//template2

        movl        $START_1+END_1+RANDOM_1, TEMP_1 // RANDOM_1 = any
                    integer
        xorl        CHECKSUM_1, CHECKSUM_1
        movl        TEMP_1, CHECKSUM_2
LABEL_1:
        addl        -END_1-RANDOM_1(TEMP_1), CHECKSUM_1
        xorl        -END_1-RANDOM_2+3(TEMP_1), CHECKSUM_2
        subl        $-RANDOM_2, TEMP_1// RANDOM_2 in [3,5]
        cmpl        $END_1+END_1+RANDOM_1, TEMP_1
        jle         LABEL_1
```

FIG. 3

$$(x+3)(y+7) \tag{1}$$
$$= \quad (x+3+0)(y+7+0) \tag{2}$$
$$= \quad (x+3+u-u_0)(y+7+w_0-w) \quad \text{iff } u = u_0 \text{ and } w = w_0 \tag{3}$$
$$= \quad (x+u+k_1)(y-w+k_2) \quad \text{where } k_1 = 3 - u0 \text{ and } k_2 = 7 + w_0 \tag{4}$$

FIG. 4

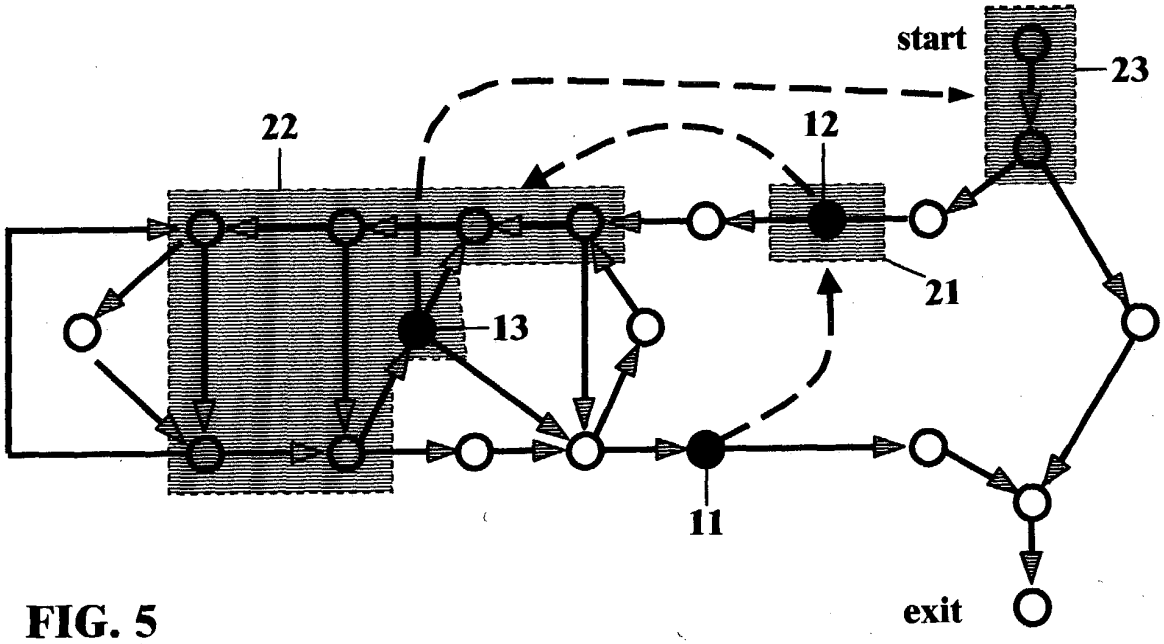


FIG. 5

```
1   main:
2           leal    -4(%esp), %esp          // %esp := %esp – 4
3           movl    %ebp, (%esp)            // mem[%esp] := %ebp
4           movl    %esp, %ebp
5           subl    $8, %esp                // %esp := %esp – 8
6           leal    -8(%ebp), %eax
7           leal    -4(%esp), %esp
8           movl    %eax, (%esp)
9           leal    -4(%esp), %esp
10          movl    $str1, (%esp)
11          leal    -4(%esp), %esp
12          movl    $next1, (%esp)          // mem[%esp] := $next1
13          jmp     scanf                   //jump to location scanf
14
15  next1:
16          addl    $8, %esp                // %esp :=%esp + 8
17          leal    -4(%esp), %esp
18          movl    -8(%ebp), %eax          // %eax := mem[%ebp-8]
19          movl    %eax, (%esp)
20          leal    -4(%esp), %esp
21          movl    $next2, (%esp)
22          jmp     pr_fact
23
24  next2
25          addl    $4, %esp
26          movl    %ebp, %esp
27          movl    (%esp), %ebp
28          leal    4(%esp), %esp
29          leal    4(%esp), %esp
30          jmp     *-4(%esp)
31
32  pr_fact:
33          leal    -4(%esp), %esp
34          movl    %ebp, (%esp)
35          movl    %esp, %ebp
36          subl    $4, %esp
37          movl    $1, -4(%ebp)
38          jmp     .L94
39
40  .L94
41          cmpl    $1, 8(%ebp)             // mem[%ebp+8] – 1 == ??
42          g       .L96                    // if ?? > 0, jmp .L96
43          jmp     .L98
44
45  .L96
46          movl    -4(%ebp), %eax
47          imul    8(%ebp), %eax           // %eax := %eax * mem[%ebp+8]
48          movl    %eax, -4(%ebp)
49          subl    $1, 8(%ebp)
50          jmp     .L94
51
52  .L98
53          leal    -4(%esp), %esp
54          movl    -4(%ebp), %eax
55          movl    %eax, (%esp)
56          leal    -4(%esp),
```

FIG. 6A

```
57              movl    $str2, (%esp)
58              leal    -4(%esp), %esp
59              movl    $next3, (%esp)
60              jmp     printf
61
62      next3:
63              addl    $8, %esp
64              movl    %ebp, %esp
65              movl    (%esp), %ebp
66              leal    4(%esp), %esp
67              leal    4(%esp), %esp
68              jmp     *-4(%esp)               // jump to addr in mem[%esp-4]
69
```

FIG. 6B

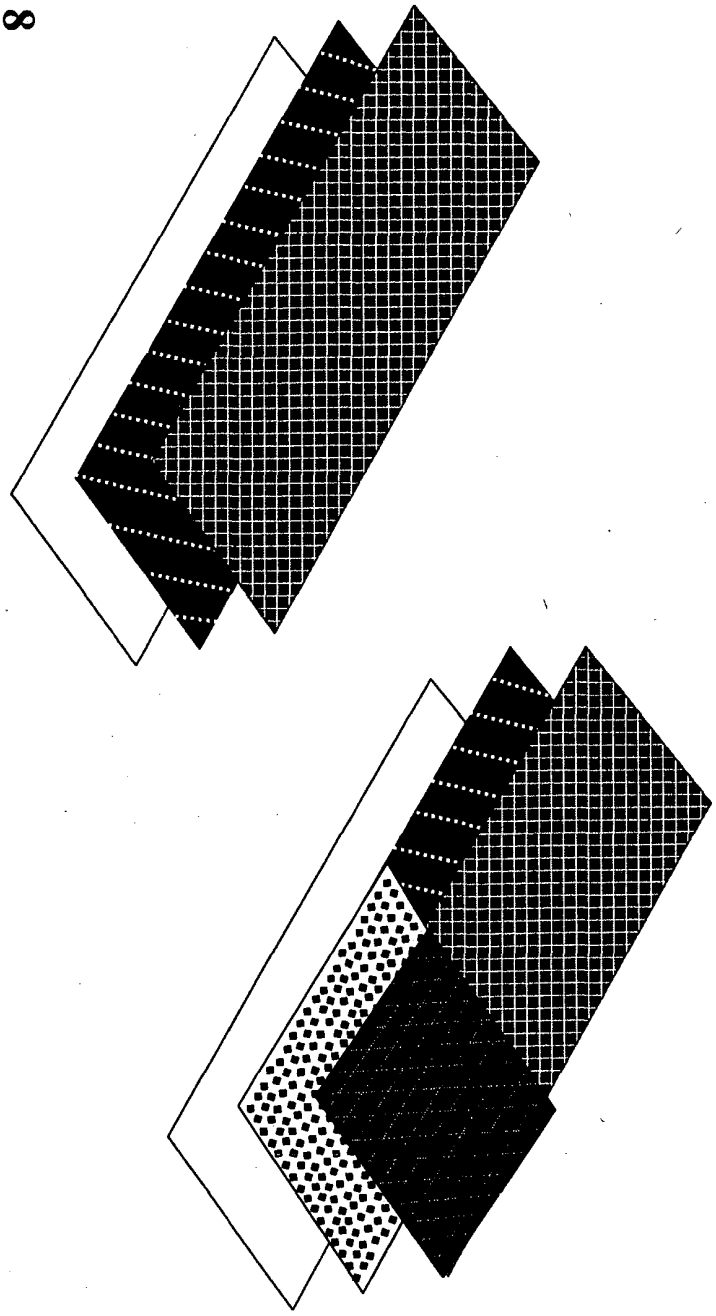
```
1   main:
2               leal    -4(%esp), %esp
3               movl    %ebp, (%esp)
4               movl    %esp, %ebp
5               subl    $8, %esp
6               leal    -8(%ebp), %eax
7               leal    -4(%esp), %esp
8               movl    %eax, (%esp)
9               leal    -4(%esp), %esp
10              movl    $str1, (%esp)
11              leal    -4(%esp), %esp
12              movl    $next1, (%esp)
13              jmp     scanf
14
15  next1:                                      // start of client
16              addl    $8, %esp
17              leal    -4(%esp), %esp
18              movl    -8(%ebp), %eax
19              movl    %eax, (%esp)
20              leal    -4(%esp), %esp
21              movl    $next2, (%esp)
22              jmp     pr_fact
23  end1:                                       // end of client
24
25  next2:
26              addl    $4, %esp
27              movl    %ebp, %esp
28              movl    (%esp), %ebp
29              leal    4(%esxp), %esp
30              leal    4(%esp), %esp
31              jmp     *-4(%esp)
32
33  pr_fact:
34              leal    -4(%esp), %esp
35              movl    %ebp, (%esp)
36              movl    %esp, %ebp
37              subl    $4, %esp
38
39              // guard installation site
40
41              movl    $100, g1
42              movl    $next1, %eax
43  guard1_1:
44              cmpl    $end1, %eax
45              jg      guard1_2
46              movl    g1, %ecx
47              addl    (%eax), %ecx
48              movl    %ecx, g1
49              addl    $3, %eax
50              jmp     guard1_1
51  guard1_2:
52
53              // end of checksumming: (g1, G!)
54
55              movl    $-G1+1, %eax            // G1 is the checksum constant
56              addl    g1, %eax
```

FIG. 7A

```
57              movl    %eax, -4(%ebp)
58              jmp     .L94
59
60      .L94:
61              leal    8+G1(%ebp), %eax
62              subl    g1, %eax
63              movl    (%eax), %eax
64              cmpl    $1, %eax
65              jg      .L96
66              jmp     .L98
67
68      .L96:
69              movl    -4(%ebp), %eax
70              imul    8(%ebp), %eax
71              movl    %eax, -4(%ebp)
72              subl    $1, 8(%ebp)
73              jmp     .L94
74
75      .L98:
76              leal    -4(%esp), %esp
77              movl    -4(%ebp), %eax
78              movl    %eax, (%esp)
79              leal    -4(%esp), %esp
80              movl    $str2, (%esp)
81              leal    -4(%esp), %esp
82              movl    $next3, (%esp)
83              jmp     printf
84
85      next3:
86              addl    $8, %esp
87              movl    %ebp, %esp
88              movl    (%esp), %ebp
89              leal    4(%esp), %esp
90              leal    4(%esp), %esp
91              jmp     *-4(%esp)
92
```

FIG. 7B

FIG. 8



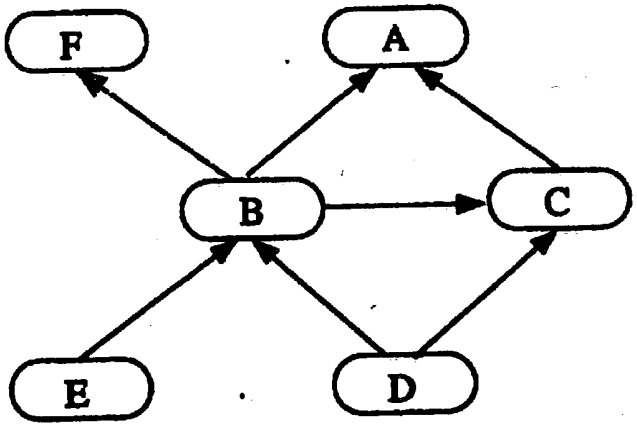


FIG. 9A

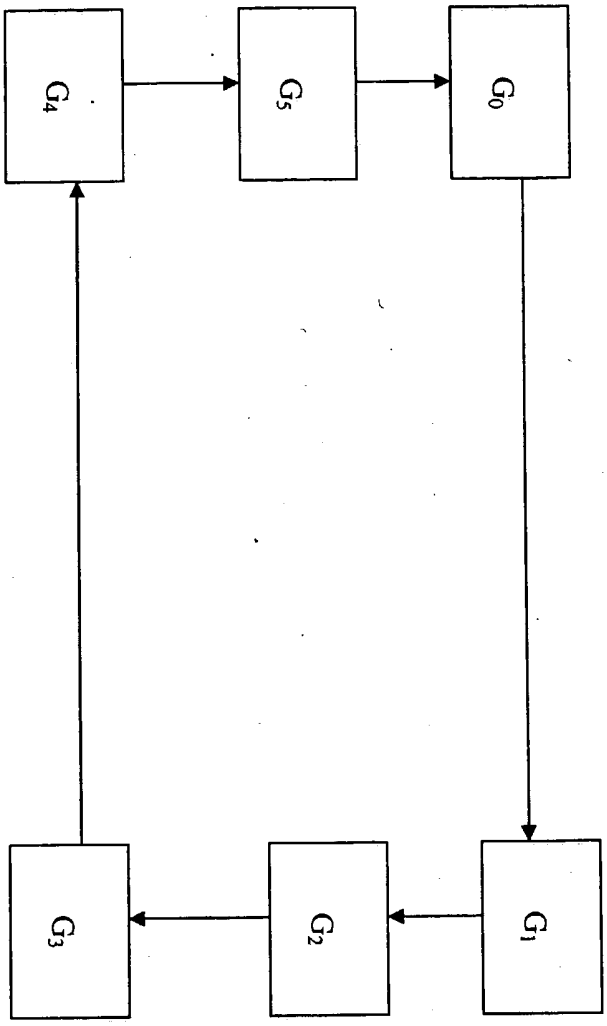


FIG. 9B

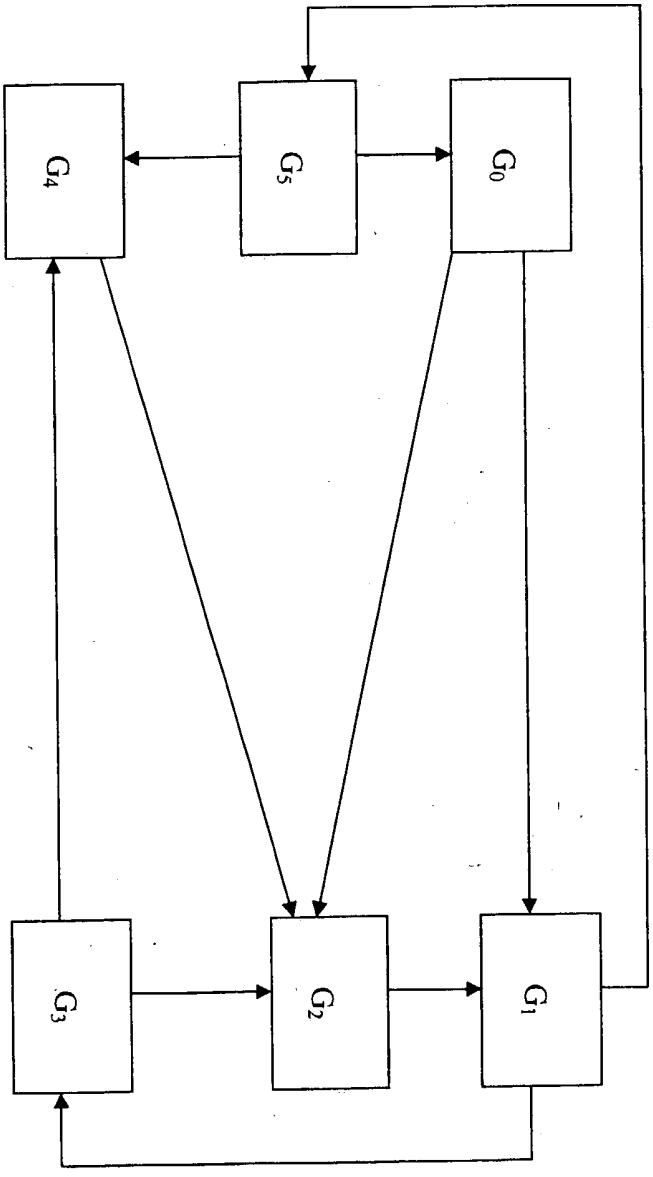


FIG. 9C

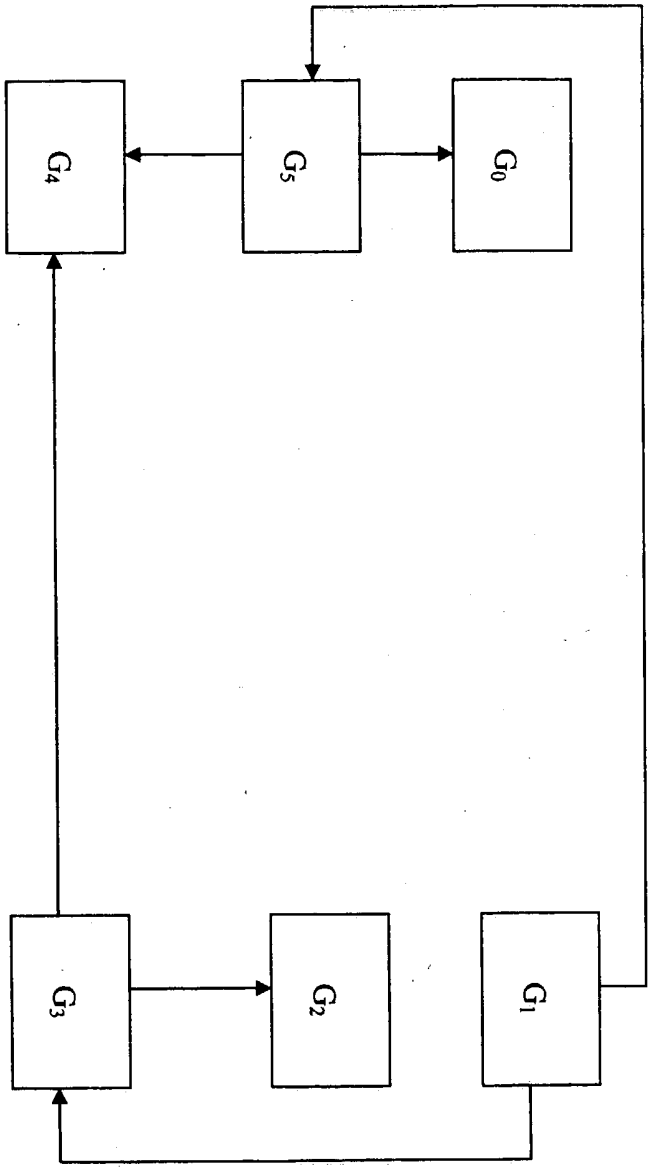


FIG. 9D

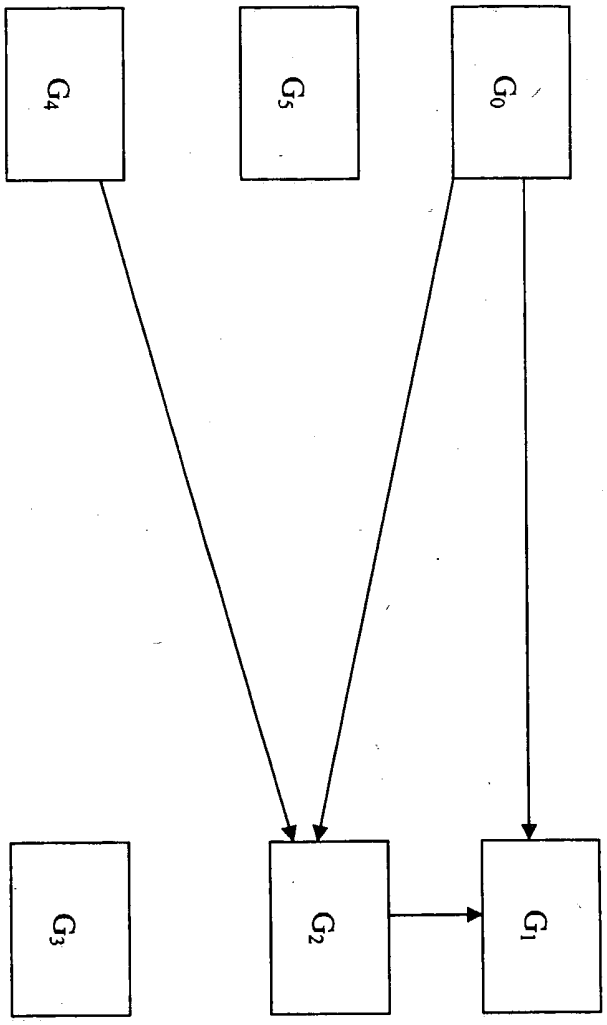


FIG. 9E

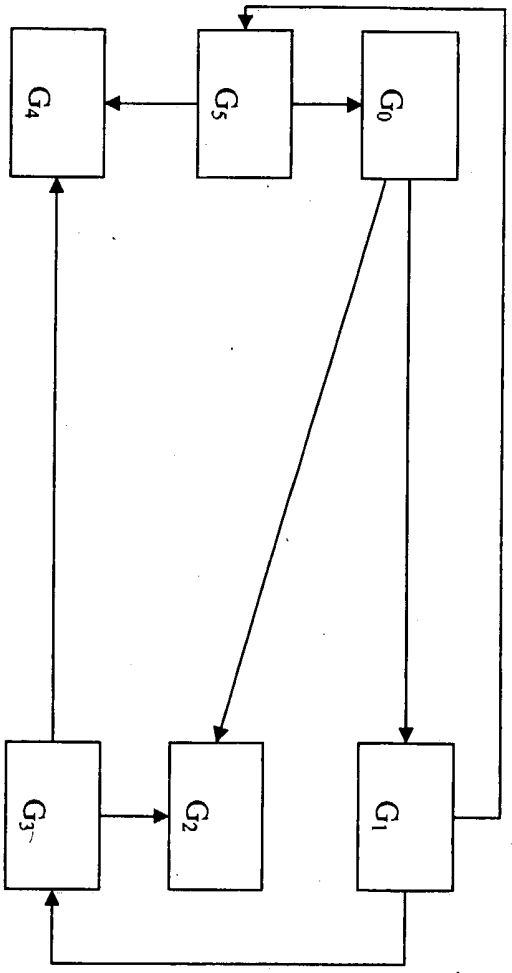
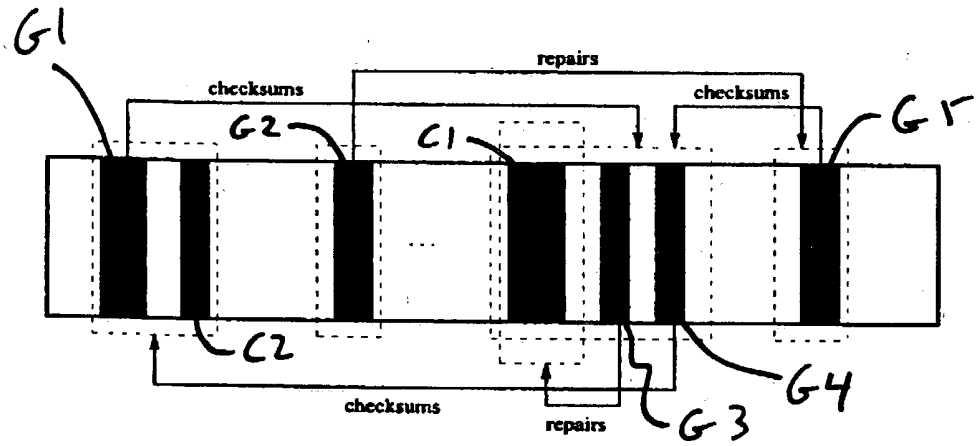
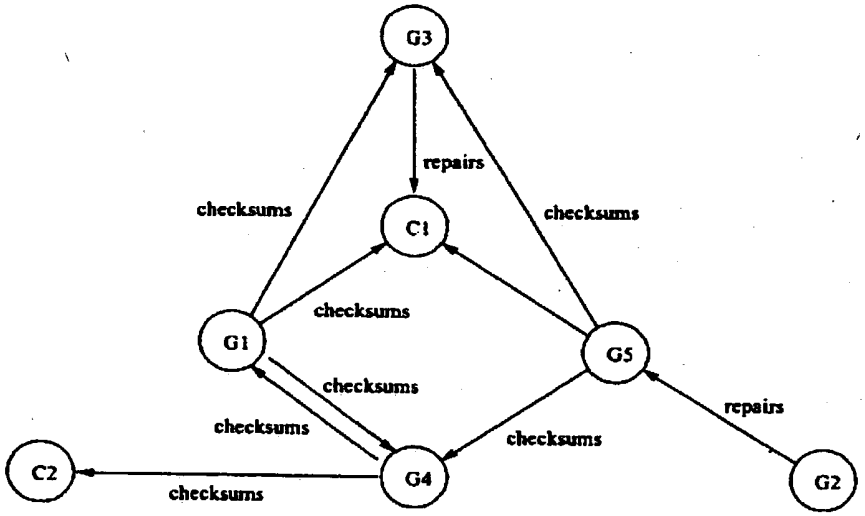


FIG. 9F



(a) Memory layout of the guarded program



(b) The corresponding guard graph

FIG. 9G

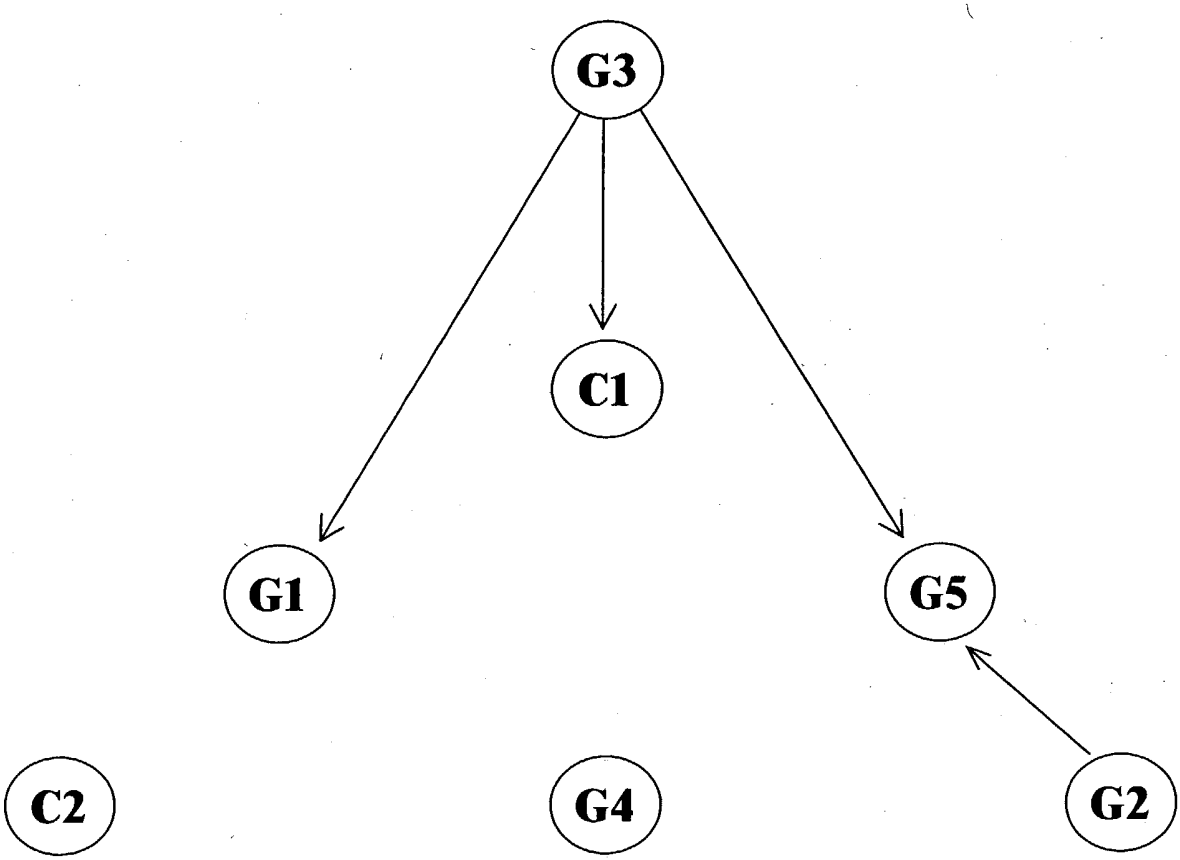


FIG. 9H

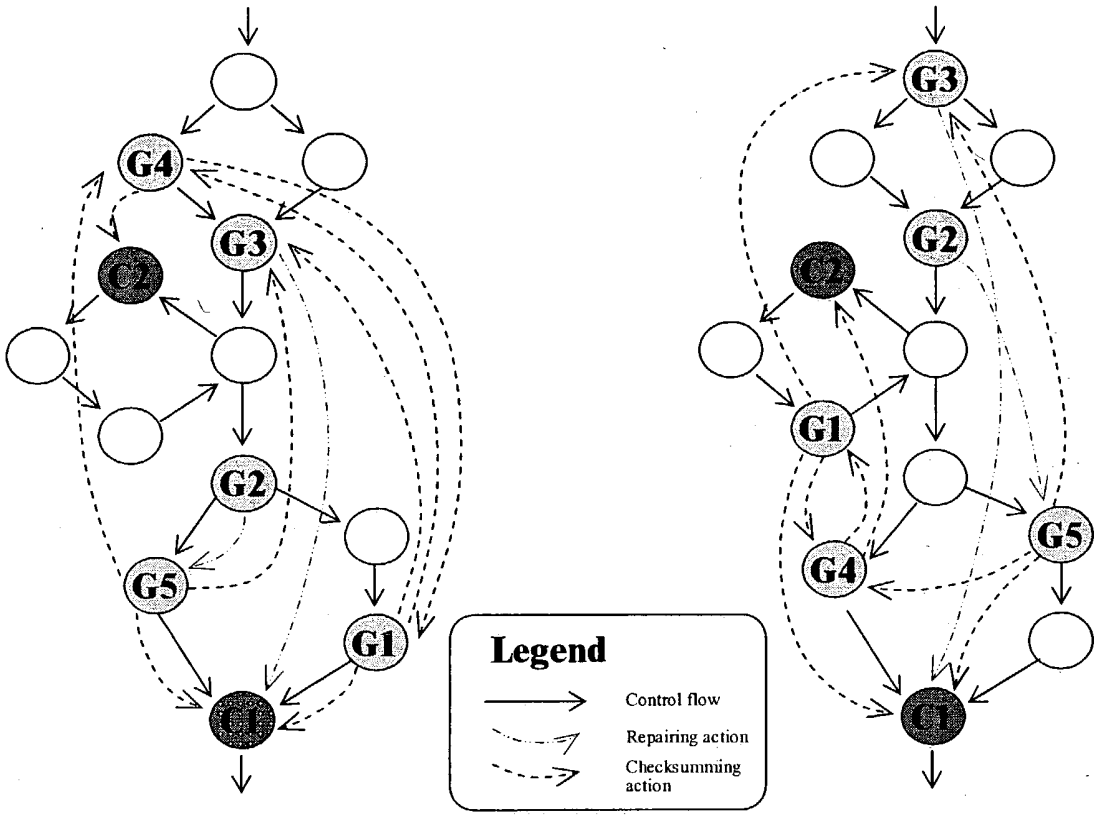

G4
G3
C2
G2
G5
G1
C1
G3
G2
C2
G1
G5
G4
C1
Legend
Control flow
Repairing action
Checksumming action

FIG. 9I

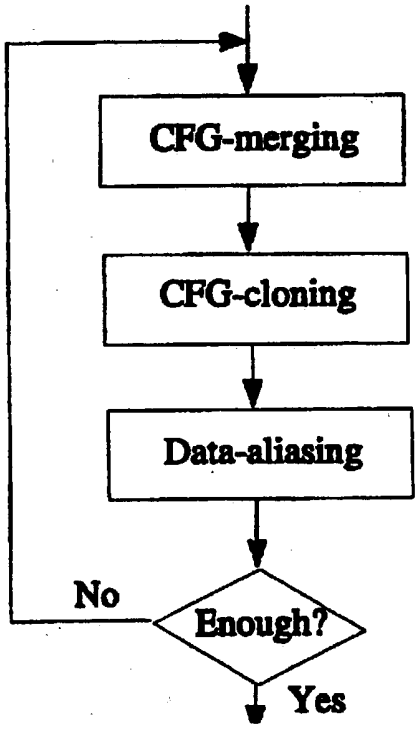


FIG. 10

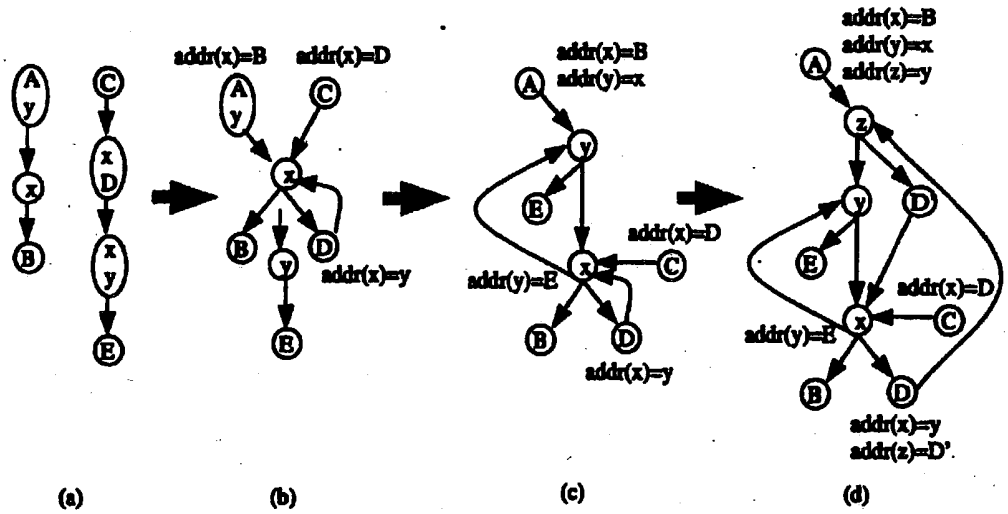

addr(x)=B
addr(x)=D
addr(x)=y
addr(y)=x
addr(y)=E
addr(x)=D
addr(x)=y
addr(x)=B
addr(y)=x
addr(z)=y
addr(x)=D
addr(y)=E
addr(x)=y
addr(z)=D'
(a)
(b)
(c)
(d)

FIG. 11

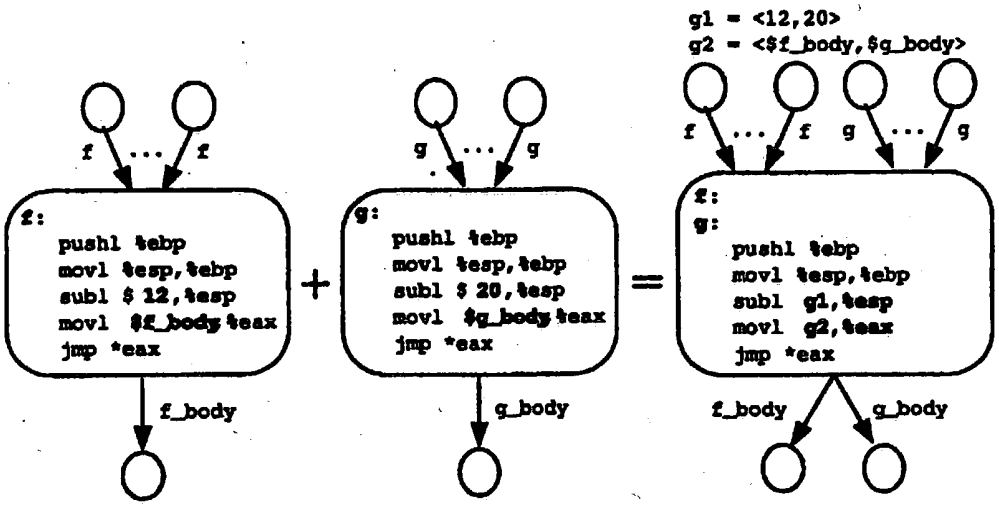

f
f
f:
pushl %ebp
movl %esp,%ebp
subl $ 12,%esp
movl $f_body,%eax
jmp *eax
f_body
g
g
g:
pushl %ebp
movl %esp,%ebp
subl $ 20,%esp
movl $g_body,%eax
jmp *eax
g_body
g1 = <12,20>
g2 = <$f_body,$g_body>
f
f
g
g
f:
g:
pushl %ebp
movl %esp,%ebp
subl g1,%esp
movl g2,%eax
jmp *eax
f_body
g_body

FIG. 12

```
1   main:
2               movl    $38, g2                 // g2=38                <38>
3               movl    $main_2+30, %eax
4               subl    g2, %eax
5               movl    %eax, g3                // g3=main_2+30-g2      <main_2-8>
6               jmp     main_1
7               // g2=<32>, g3=<main_2-8>
8   main_1:
9   pr_fact:
10              leal    -4(%esp), %esp
11              subl    $30, g2                 // g2=g2-30             <8,4>
12              movl    %ebp, (%esp)
13              movl    g2, %ebp
14              addl    %ebp, g3                // g3=g3+g2             <main_2,pr_fact_1>
15              movl    %esp, %ebp
16              subl    g2, %esp
17              movl    g3, %eax
18              jmp     *%eax
19              // g1=<,?> g2=<8,4>, g3=<main_2,pr_fact_1>
20  main_2:
21              addl    $26, g2                 // g2=g2+26             <34>
22              leal    -8(%ebp), %eax
23              leal    -4(%esp), %esp
24              movl    %eax, (%esp)
25              leal    -4(%esp), %esp
26              movl    $str1, (%esp)
27              leal    -4(%esp), %esp
28              movl    $next1, (%esp)
29              jmp     scanf
30              // g2=<34>
31  next1:      // client start
32              addl    $8, %esp
33              leal    -4(%esp), %esp
34              movl    $pr_fact_1-38, %eax
35              addl    g2, %eax
36              movl    %eax, g3                // g3=g2+pr_fact_1-38   <pr_fact_1-4>
37              movl    -8(%ebp), %eax
38              movl    %eax, (%esp)
39              leal    -4(%esp), %esp
40              movl    $next2, (%esp)
41              jmp     pr_fact
42              // g2=<34>, g3=<pr_fact_1-4>
43  end1:       // client end
44  next2:
45              addl    $4, %esp
46              movl    %ebp, %esp
47              movl    (%esp), %ebp
48              leal    4(%esp), %esp
49              leal    4(%esp), %esp
50              j,mp    *-4(%esp)
51  pr_fact_1:          // guard installation site
52              movl    $100, g1
53              movl    $next1, %eax
54              jmp     guard1_1
55              // g1=<?>
56  guard1_1:
```

FIG. 13A

```
57                  cmpl        $end1, %eax
58                  jg          guard1_2
59                  jmp         guard1_3
60                  // g1=<?>
61  guard1_3:
62                  movl        g1, %ecx
63                  addl        (%eax), %ecx
64                  movl        %ecx, g1
65                  addl        $3, %eax
66                  jmp         guard1_1
67                  // g1=<?>
68  guard1_2:
69                  // end of checksumming: (g1, G1)                    // g1=<G1>
70                  movl        $-G1+1, %eax
71                  addl        g1, %eax
72                  movl        %eax, -4(%ebp)
73                  jmp         .L94
74                  // g1=<G1>
75  .L94:
76                  leal        8+G1(%ebp), %eax
77                  subl        g1, %eax
78                  movl        (%eax), %eax
79                  cmpl        $1, %eax
80                  jg          .L96
81                  jmp         .L98
82                  // g1=<G1>
83  .L96:
84                  movl        -4(%ebp), %eax
85                  imul        8(%ebp), %eax
86                  movl        %eax, -4(%ebp)
87                  subl        $1, 8(%ebp)
88                  jmp         .L94
89  .L98:
90                  leal        -4(%esp), %esp
91                  movl        -4(%ebp), %eax
92                  movl        %eax, (%esp)
93                  leal        -4(%esp), %esp
94                  movl        $str2, (%esp)
95                  leal        -4(%esp), %esp
96                  movl        $next3, (%esp)
97                  jmp         printf
98  next3:
99                  addl        $8, %esp
100                 movl        %ebp, %esp
101                 movl        (%esp), %ebp
102                 leal        4(%esp), %esp
103                 leal        4(%esp), %esp
104                 jmp         *-4(%esp)
105
```

FIG. 13B

```
1   main:
2               movl    $38, g2                         // g2=38                <38>
3               movl    $scanf-1000, g5                 // g5=scanf-1000        <scanf-1000>
4               movl    $main_2+30, %eax
5               subl    g1, %eax
6               movl    %eax, g3                        // g3=main_2+30-g2      <main_2-8>
7               jmp     main_1
8               // g2=<38>, g3=<main_2-8>, g5=<scanf-1000>
9   main_1:
10  pr_fact:
11              leal    -4(%esp), %esp
12              subl    $30, g1                         // g2=g2-30             <8,4>
13              movl    %ebp, (%esp)
14              movl    g2, %ebp
15              addl    %ebp, g3                        // g3=g3+g2             <main_2,pr_fact_1>
16              movl    %esp, %ebp
17              subl    g2, %esp
18              movl    $1000, %eax
19              addl    g5, %eax
20              movl    %eax, g4                        // g4=g5+1000           <scanf>
21              movl    g3, %eax
22              jmp     *%eax
23              // g1=<,?> g2=<8,4>, g3=<main_2,pr_fact_1., g4=<scanf,>
24  main_2:
25              addl    $26, g2                         // g2=g2+26             <34>
26              movl    $next1-794320, %eax
27              addl    g2, %eax
28              movl    %eax, g1                        // g1=g2+next1-794320   <next1-794286>
29              leal    -8(%ebp), %eax
30              leal    -4(%esp), %esp
31              movl    %eax, (%esp)
32              leal    -4(%esp), %esp
33              movl    $str1, (%esp)
34              jmp     main_2_1
35              // g1=<next1-794286>, g2=<34>, g4=<scanf>
36  next1:      // client start
37              addl    $8, %esp
38              leal    -4(%esp), %esp
39              movl    $pr_fact_1-38, %eax
40              addl    g2, %eax
41              movl    %eax, g3                        // g3=g2+pr_fact_1-38   <pr_fact_1-4>
42              addl    $next2-794286-next1, g1         // g1=g1+next2-794286-next1 <next2-794286>
43              movl    $pr_fact, g4                    // g4=pr_fact           <pr_fact>
44              movl    -8(%ebp), %eax
45              movl    %eax, (%esp)
46              jmp     next1_1
47              // g1=<next2-794286>, g2=<34>, g3=<pr_fact_1-4>, g4=<pr_fact>
48  next1_1:
49  main_2_1:
50  .L98_1:
51              leal    -4(%esp), %esp
52              addl    $794286, g1                     // g1=g1+794286         <next1>
53              movl    g1, %eax
54              movl    %eax, (%esp)
55              movl    g4, %eax
56              jmp     *%eax
```

FIG. 14A

```
57                  // g1=<next2,next1,next3>, g2=<34,34,>, g3=<pr_fact_1-4,,>,
58                  // g4=<pr_fact,scanf,printf>, g5=<?>
59  end1:           // client end
60  next2:
61                  addl        $4, %esp
62                  movl        %ebp, %esp
63                  movl        (%esp), %ebp
64                  leal        4(%esp), %esp
65                  leal        4(%esp), %esp
66                  jmp         *-4(%esp)
67  pr_fact_1:      // guard installation site
68                  movl        $100, g1                    //                  <?>
69                  movl        $next1, %eax
70                  jmp         guard1_1
71                  // g1=<?>
72  guard1_1:
73                  cmpl        $end1, %eax
74                  jg          guard1_2
75                  jmp         guard1_3
76                  // g1=<?>
77  guard1_3:
78                  movl        g1, %ecx
79                  addl        (%eax), %ecx
80                  movl        %ecx, g1
81                  addl        $3, %eax
82                  jmp         guard1_1
83                  // g1=<?>
84  guard1_2:
85                  // end of checksumming: (g1,G1)
86                  movl        $printf-G1, %eax
87                  addl        g1, %eax
88                  movl        %eax, g4                    // g4=g1+printf-G1
89                  movl        $-G1+1, %eax
90                  addl        g1, %eax
91                  movl        %eax, -4(%ebp)
92                  jmp         .L94
93                  // g1=<g1>, g4=<printf>
94  .L94:
95                  leal        8+G1(%ebp), %eax
96                  subl        g1, %eax
97                  movl        (%eax), %eax
98                  cmpl        $1, %eax
99                  jg          .L96
100                 jmp         .L98
101                 // g1=<g1>, g4=<printf>
102 .L96
103                 movl        -4(%ebp), %eax
104                 imul        8(%ebp), %eax
105                 movl        %eax, -4(%ebp)
106                 subl        $1, 8(%ebp)
107                 jmp         .L94
108                 // g4=<printf>
109 .L98:
110                 addl        $-G1+next3-794286, g1       // g1=g1-G1+next3-794286    <next3-794286>
111                 leal        -4(%esp), %esp
112                 movl        -4(%ebp), %eax
```

FIG. 14B

```
113                 movl    %eax, (%esp)
114                 leal    -4(%esp), %esp
115                 movl    $str2, (%esp)
116                 jmp     .L98_1
117                 // g1=<next3-794286>, g4=<printf>
118     next3:
119                 addl    $8, %esp
120                 movl    %ebp, %esp
121                 movl    (%esp), %ebp
122                 leal    4(%esp), %esp
123                 leal    4(%esp), %esp
124                 jmp     *-4(%esp)
125
```

FIG. 14C

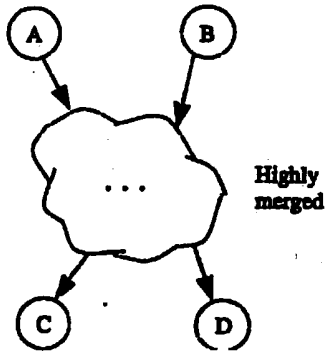


FIG. 15

FIG. 16

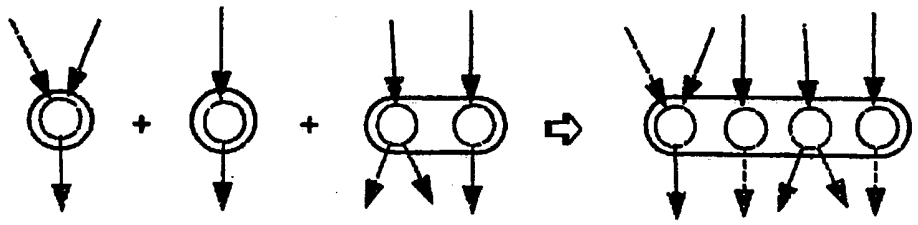


FIG. 17

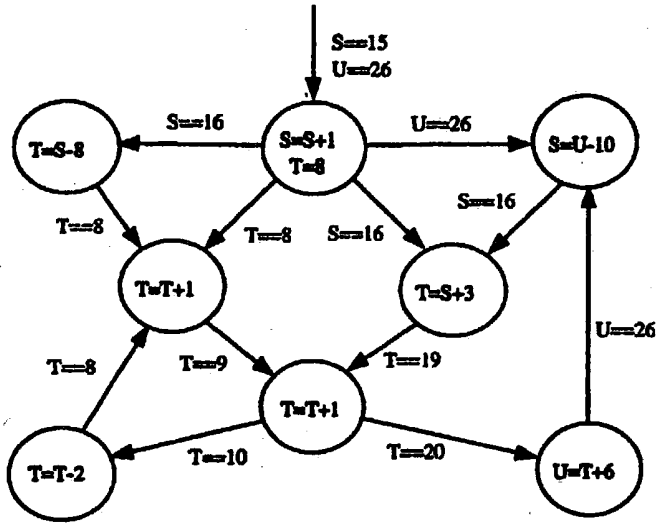

S==15
U==26
S==16
U==26
T=S-8
S=S+1
T=8
S=U-10
T==8
T==8
S==16
S==16
T=T+1
T=S+3
U==26
T==8
T==9
T==19
T=T+1
T=T-2
T==10
T==20
U=T+6

FIG. 18

```
Procedure precompute (variable v, link-nodes {x_1,...,x_n},
                      constants {c_1,...,c_n})

    Set live(v,x_i) = TRUE and value(v,x_i) = c_i for all i = 1,...,n;

    While (there is a link-node x and a variable v such that
        value(v,x) is defined but done(v,x)==FALSE)

        Let X = {x_1,...,x_n} be the entire set of link-nodes in the
            same basic block, say B, that contains x;
        Let t be the point within B for inserting evolve( );

        If (no evolve( ) has previously been chosen for B)
            Choose a mathematical function evolve(U), where U is a (possibly
             empty) set of (new) global variables, with the following properties:
            (1)  No u in U is reserved (i.e. no u in U that, for some z in pred-
                 links(X), live(u,z)==TRUE but value(u,z) is undefined);
            (2)  For any x_i in X where value(v,x_i) is defined, the common
                 evolve(U) is able to fulfill value(v,x_i) by setting value(u,z)
                 appropriately, for any u in U and z in pred-links(x_i) with
                 unseen(u,z,t)==TRUE;
            (3)  For all x_i in X where value(v,x_i) is undefined, the same
                 evolve(U) is possible to fulfill any desired value for any future
                 definition of value(u,x_i);

        End if

        If (evolve( ) is newly chosen and is not the trivial identity function)
            Insert code at t of B for computing v=evolve(U);
        End if

        For (all u in U and z in pred-links(x) where unseen(u,z,t)==TRUE)
            Set live(u,z) = TRUE and value(u,z) equal to some values such that these
            new values, together with other values of U already set along the paths to t
            through z, satisfy value(v,x)==evolve(U);
        End for

        For (each x_i in X where value(v,x_i) is underfined, and each u in U and z in
        pred-links(x_i) where unseen(u,z,t)==TRUE)
            Set live(u,z) = TRUE;
        End for

        Set done(v,x) = TRUE;
        End while
End procedure
```

FIG. 19A

```
Procedure unseen(variable v, link-node z, program point t)
    If (value(v,z) is undefined, and at the basic block that contains t, v is not defined in the
    code before t)
        return TRUE;
    Else
        return FALSE;
    End procedure
```

FIG. 19B

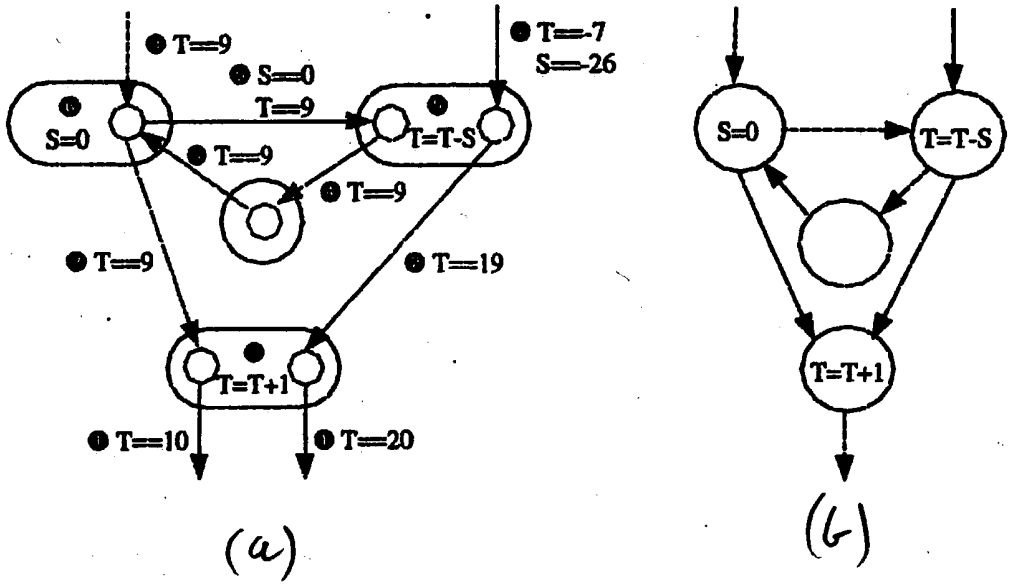


FIG. 20

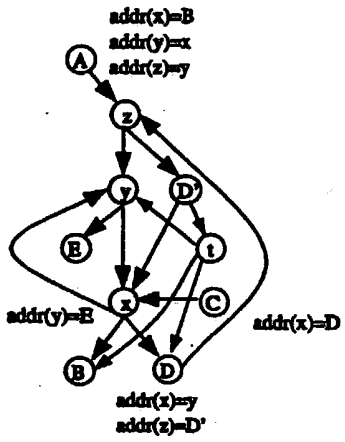

addr(x)=B
addr(y)=x
addr(z)=y
A
z
y
D
E
t
x
C
addr(y)=E
addr(x)=D
B
D
addr(x)=y
addr(z)=D'

FIG. 21

```
// (a) before change
        . . .
        jmp         .L24

// (b) after change
        . . .
        cmpl        %eax, (%esp)        // args are randomly selected
        jl          .L013               // clone
        jmp         .L24
```

FIG. 22

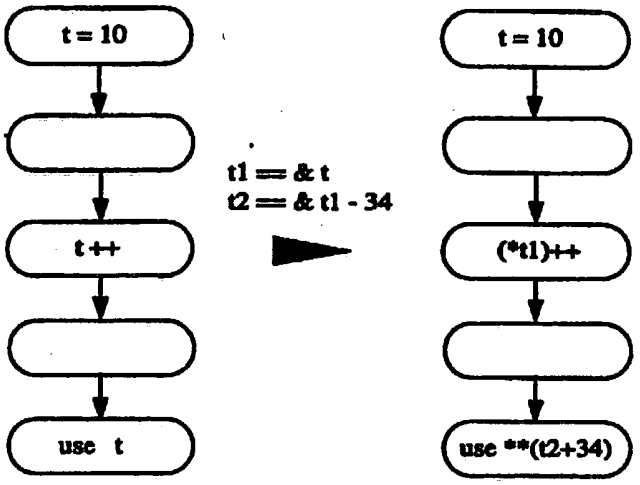


FIG. 23

tag	*sh f*	*E(len + sh f)*	*E(msg + sh f)*

FIG. 24

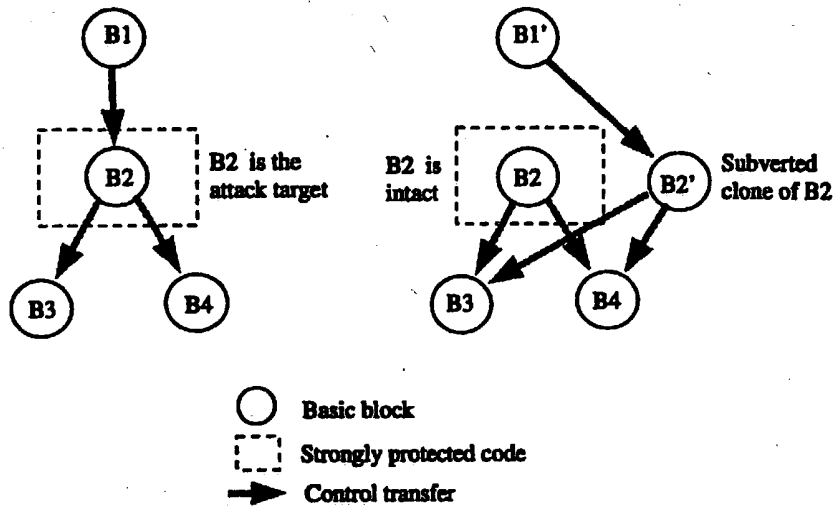

B1
B2
B3
B4
B2 is the attack target
B1'
B2'
B2 is intact
Subverted clone of B2
Basic block
Strongly protected code
Control transfer

FIG. 25

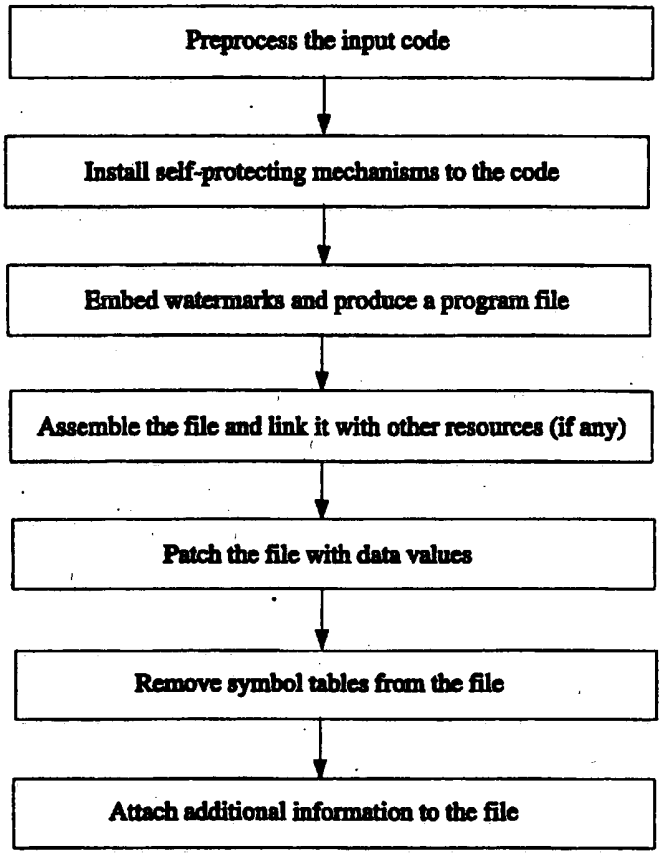

Preprocess the input code
Install self-protecting mechanisms to the code
Embed watermarks and produce a program file
Assemble the file and link it with other resources (if any)
Patch the file with data values
Remove symbol tables from the file
Attach additional information to the file

FIG. 26

High-level instructions		*Simpler instructions*
call *operand* next: . . .		pushl $next jmp *operand* next: . . .
ret		leal 4(%esp), %esp jmp * −4(%esp)
enter		pushl %ebp movl %esp, %ebp
leave		movl %ebp, %esp popl %ebp
pushl *operand*		leal −4(%esp), %esp movl *operand*, (%esp)
popl *operand*		movl (%esp), *operand* leal 4(%esp), %esp

FIG. 27

Software Program Code	Encrypted customization parameters	Digital signature

FIG. 28

Wrong password		*After "bypassing" password*
password: **abc** Invalid password!		password: **abc** n ? **100000** next prime = 100001
Right password		*After further "corrections"*
password: **opensesame** n ? **100000** next prime = 100003		password: **abc** n ? **100000** Segmentation Fault (core dumped)

FIG. 29

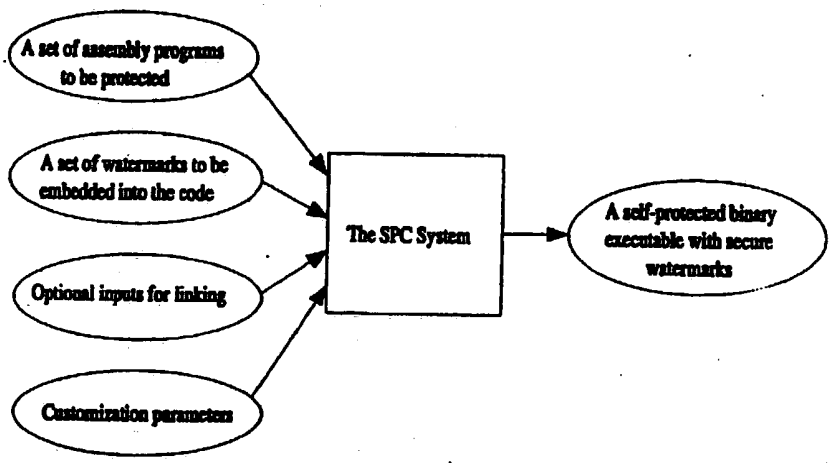

A set of assembly programs to be protected
A set of watermarks to be embedded into the code
Optional inputs for linking
Customization parameters
The SPC System
A self-protected binary executable with secure watermarks

FIG. 30